EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN - ACCELERATORS AND TECHNOLOGY SECTOR

CERN-ATS 2011-009

**ACTIVE COMPENSATION OF FIELD ERRORS
WITHIN ± 2 PPM IN SUPERCONDUCTING MAGNETS**

Pasquale Arpaia^{1,2}, Lucio Fiscarelli^{1,2}, Giuseppe Montenero^{1,2}, Louis Walckiers²

1 Department of Engineering, University of Sannio, Benevento, Italy

2 Department of Technology, CERN, Geneva, Switzerland.

Abstract

A system for the active compensation of magnetic field errors within ± 2 ppm relative to the main field in superconducting magnets is proposed. A high-performance rotating coils system is exploited in order to combine high time resolution and integral field measurements. The compensation is based on an enhanced characterization of the corrector magnets and the measured field: this allows the system to be used as off-line reference in accelerator facilities. As an experimental case study, the measurement system and the procedure for compensating field errors of dipole magnets of the Large Hadron Collider at the European Organization for Nuclear Research (CERN) are illustrated.

CERN-ATS-2011-009
13/05/2011

Published in Nuclear Instruments and Methods in Physics Research A
2011

Geneva, Switzerland

May 2011

Active compensation of field errors within ± 2 ppm in superconducting magnets

Pasquale Arpaia^{1,2}, Lucio Fiscarelli^{1,2}, Giuseppe Montenero^{1,2}, Louis Walckiers²

¹ Department of Engineering, University of Sannio, Corso Garibaldi 107, 82100 Benevento, Italy.
Ph : +39 0824 305804-17, Fax: +39 0824 305840, E-mail: arpaia@unisannio.it

² Dept. of Technology, Group of Magnets Superconductors Cryostats – Magnetic Measurements, CERN,
CH 1211, Genève 23, Switzerland.
Ph : +41 22 76 72645, Fax: +41 22 76 76230, E-mail: Giuseppe.Montenero@cern.ch

Abstract – *A system for the active compensation of magnetic field errors within ± 2 ppm relative to the main field in superconducting magnets is proposed. A high-performance rotating coils system is exploited in order to combine high time resolution and integral field measurements. The compensation is based on an enhanced characterization of the corrector magnets and the measured field: this allows the system to be used as off-line reference in accelerator facilities. As an experimental case study, the measurement system and the procedure for compensating field errors of dipole magnets of the Large Hadron Collider at the European Organization for Nuclear Research (CERN) are illustrated.*

Keywords – *Magnetic Measurements Systems, Superconducting Magnets, Field Errors.*

I. INTRODUCTION

The evolution of particle accelerators has always stimulated new technology developments in many areas of research [1]. In particular, the continuous demand for increasing collision energy has led to a remarkable research effort in superconducting magnets. Nowadays, the predominant material used in superconducting magnet coils of high-performance accelerators is NbTi, owing to its straightforward coil winding and cost effectiveness [2]-[3]. The advent of a reliable Nb₃Sn technology will increase the maximum value of the generated field to beyond 10 T for future needs [4]-[5]. However, superconducting magnets are affected by higher-order multipoles and anomalous dynamic behavior of the magnetic field [6]. In particle accelerators, the higher order multipoles present in the main dipole and quadrupole magnets must be compensated by corrector

magnets to avoid particle loss or degradation of the beam lifetime. Undesired dynamic effects in the main dipole magnets lead to a field uncertainty of hundreds of ppm relative to the main field component. In addition, these effects are dominant at low field, i.e. during particle injection and acceleration when the emittance of the particle beam is large. In literature, this undesired dynamic behavior is mainly referred to as *decay* and *snapback* of the sextupole and decapole field components, in dipoles, and of the dodecapole field components, in quadrupoles [7]-[8]. In particular, the sextupole changes the beam chromaticity [9], leading to beam instability (abnormal oscillation of particles' trajectories), and then to particle loss.

In the past years, the requirements to more strictly suppress field errors affecting the operation of high-quality accelerators have been successfully met by several control systems based on either feed-forward or direct feedback mechanisms [10-17]. The main goal is to accurately tune the higher-order - namely sextupole, decapole, and dodecapole - superconducting corrector magnets. The Hadron Electron Ring Accelerator (HERA) [10] was equipped with a measurement system based on rotating coils (giving a resolution of 20 ppm). It was mounted in reference magnets electrically connected in series with the main magnet chain in order to assess the contribution of the field multipoles from the main dipoles during the machine operation [11]. The insufficient metrological performance of this system pointed out the need for combining the data from reference magnets with direct beam measurements. For the Tevatron, the Proton-Antiproton Collider at Fermilab [12], the principal method of compensating undesired magnet multipoles is a feed-forward system [13]. A feedback system based on reference magnets was considered too expensive initially [14], and therefore, the feed forward system was improved by carrying out off-line measurements on several spare magnets [15]. This highlighted the need for enhanced measurement systems able to respond to the more and more stringent requirements dictated by the machine. For the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN), a mixed system based on both a feed-forward mechanism and feedback from beam diagnostics is implemented [16]. The feed forward mechanism, the *field description model of the LHC* (FiDel) [17], provides tools for predicting main and multipole magnetic field errors of the magnets in operational conditions, thereby reducing the required range of the feedback loops based on beam diagnostics [18]. However, the most recent experimental results from machine runs [19] have highlighted the need for improving the compensation to permit the full beam luminosity to be reached. The beam chromaticity will need to be controlled within 1 unit,

corresponding to ± 2 ppm of mismatch on the sextupole at a magnet reference radius of 17 mm in the 8.3 T twin aperture LHC dipoles [20]. The ratio between the bending strength of the main dipole magnets and the focusing strength of the quadrupole must be controlled within 15 ppm in order to limit tune changes to below 10^{-2} during the whole beam cycle. Measurement systems existing at the time of the LHC construction are not suitable, due mainly to a too low resolution, either in time domain [21] (harmonic coil techniques), or in space domain [22] (Hall probe detectors).

In this paper, a measurement system based on rotating coils, capable of actively compensating multipole field errors with a maximum residual value of ± 2 ppm relative to the main field is proposed. The system keeps both the advantages of high time resolution and field measurements averaged over the full length of the magnets. In particular, in Section II, the theoretical background on field errors is reported, and in Section III, the proposed compensation procedure is presented. In Section IV, the measurement system set-up is described, and in Section V, an experimental case study related to the compensation of sextupole error in LHC dipole magnets at CERN is discussed.

II. THEORETICAL BACKGROUND ON FIELD ERRORS

The field in magnets of high-energy accelerators can be expressed by means of a 2-D complex harmonic expansion giving the multipoles integrated over the magnet length:

$$\mathbf{B}(x, y, t) = \sum_{k=1}^{\infty} [B_k(t) + jA_k(t)] \left(\frac{x+jy}{R_{ref}} \right)^{k-1} \quad (1)$$

where R_{ref} is the reference radius of the magnet, and, by convention B_k and A_k are the normal and skew field harmonic components, respectively. If the main field is either B_i or A_i , the magnet is referred as normal or skew of i -th order. Therefore, in (1), the components with $k \neq i$ are the undesired harmonic content or the field errors [23].

In superconducting magnets, the field errors are of the order of 10^{-4} of the main field at the reference radius R_{ref} corresponding to the useful aperture for the beam. Therefore, (1) can be expressed as:

$$\mathbf{B}(x, y, t) = B_i(t) \sum_{k=1}^{\infty} \left[\frac{b_k(t) + ja_k(t)}{10^6} \right] \left(\frac{x+jy}{R_{ref}} \right)^{k-1} \quad (2)$$

where B_i is the main field, and b_k and a_k the multipole field error expressed in ppm, namely

$$(b_k|a_k) = \frac{(B_k|A_k)}{B_i} \times 10^6.$$

The quality of the field is degraded by a few factors rendered unavoidable by the manufacturing process. The main sources, geometrical errors, iron saturation, superconductor magnetization, and coupling currents, lead to a nonlinearity and consequent unwanted multipole terms in the central field of the magnet bore [22-24]. Geometrical errors are minimized by careful design of the magnet cross section (iron yoke and coils). Saturation of the iron yoke at high fields results in multipole changes. Superconductor magnetization and coupling currents are related to the rate of change of the magnetic field: the magnetization is induced at the periphery of superconducting filaments and the coupling currents depend on inter-strand cable resistance. The multipole content can be modeled [25] and corrected by means of a suitable compensation scheme, namely by placing additional corrector magnets on the main winding, designed to provide a field strength equal and opposite to the multipole errors [26]. Detailed measurements are mandatory to build accurately enough these models, in particular for the dynamic or ramp rate induced effects. The challenging task is to control the field of the correctors accurately in order to lower the residual value of the field errors as much as possible along the magnet length as a whole during its operation.

III. THE ACTIVE COMPENSATION

The basic idea of the proposed compensation is to cancel out the cumulated effect of the field multipoles unavoidable in superconducting magnets by finely tuning the field of the corrector magnets. The exact value of the compensating current required to power the correctors is to be computed from integral field measurements with a fine resolution over time. The generation of a field equal and opposite in sign to that of the unwanted multipole requires a high degree of accuracy (less than ± 1 ppm), a fine resolution over time for the measurement of the field errors in the magnet, and the determination of the transfer function of the corrector magnet. Synchronization at 20 ms of the magnet currents allows the residual mismatch between the field multipoles generated in the main and in the corrector magnets to be minimized.

The abovementioned requirements lead to the definition of an effective compensation procedure exploiting the features of a high-performance and fast rotating measurement system [27].

In the following, (i) the *analytical formulation*, (ii) the *system architecture*, and (iii) the *procedure* governing the proposed active compensation are illustrated.

A. Analytical Formulation

The aim of the proposed compensation is to maintain the unwanted field multipoles below a few ppm, along the length of the superconducting magnet as a whole. Thus, the first step is to compute the integrated multipole as a function of time from the measurement data:

$$\bar{C}_k(t) = \sum_{q=1}^n c_{q,k}(t) \left[\sum_{p=1}^{m(q)} (L_{pq} + bs) \right] \quad [Tm] \quad (3)$$

where $c_{q,k}$ is the value of the k -th undesired harmonic either normal (b_k) or skew (a_k) (2), measured synchronously by the same encoder trigger source by means of n series of $m(q)$ harmonic coils (referred as n “supersegments”), and where $(L_{pq} + bs)$ is the length of the p -th harmonic coil segment of the q -th supersegment of the measuring shaft, with bs the blank space between segments [21].

Once the integral value of the desired component is available from (3), the current for the corrector magnet is computed:

$$I_{k,Correction}(t) = -\frac{\bar{C}_k(t)}{TF_k} \quad [A] \quad (4)$$

where TF_k is the transfer function of the corrector magnet of order k -th required to compensate the field error into the main magnet. TF_k is computed from the results of field characterization measurements as:

$$TF_k = \text{mean}_t \left(\frac{\bar{C}_{k,corr}(t)}{I(t)} \right) \quad [Tm/A] \quad (5)$$

namely, the mean of the ratio of the measured integral main field $\bar{C}_{k,corr}$ of the corrector, for the corresponding supersegment, and the powering current $I(t)$. The measurement is carried out by cycling the current from 0 A up to the maximum value acceptable by the corrector, followed by a downwards excursion to the opposite minimum and then back to 0 A.

Without compensation, Eq. (3) defines the unwanted multipole integrated over the length of the main magnet under test. The measurement of the corrector magnet, when powered, is covered by a supersegment, so that (3) evaluates the compensation.

B. System Architecture

In Fig. 1, the architecture of the proposed compensation system is depicted. For the sake of clarity, the block diagram refers to a generic scenario where the unwanted multipoles in a

superconducting magnet, affected by $e=1, \dots, d$ errors, either normal or skew of order $k_l \in \{k_1, \dots, k_d\}$, are to be compensated.

Figure 1 Architecture of the proposed compensation system.

The field of the magnet under test is acquired, during a powering cycle, by means of a measurement system based mainly on a high-speed rotating shaft holding the measurement coils and on high-accuracy Fast Digital Integrators [28]-[29]. The integrated signal, i.e. the magnetic flux, from the n series of $m(q)$ harmonic coils is analysed in order to estimate the desired field multipoles as a function of time, (3), with a sampling rate defined by the encoder. Thereafter, the resulting multipole terms in the space domain are used to produce the required current for the L corrector magnets (corrector magnets of $k_l \in \{k_1, \dots, k_L\}$ order), (4) (correction procedure). Once the correction currents are computed, the magnet and the correctors are powered.

C. Procedure

The procedure of the proposed active compensation is summarized in the flowchart of Fig. 2. The first step is to define the current pre-cycle of the particular magnet under test (MUT) because the field multipoles depend strongly on its magnetization history. The subsequent cycle allows the multipoles to be estimated as a function of time (without compensation): the MUT is powered and the measurement system is enabled (*Start of the harmonic coil measurement*). Then, the correction process computes the currents required to power the correctors (*Data*

Analysis and Correction Procedure). During the first iteration, the estimated current cycles are stored, and, from the second run, the new ones are defined as the difference between those first stored and the second ones (with a refinement by successive approximations). The procedure ends when the measured residual errors h_{kl} are below the target (of. 2 ppm) at any time during the powering cycle.

Figure 2 Flow chart of the proposed compensation procedure.

IV. THE MEASUREMENT SYSTEM

The effectiveness of the proposed approach was tested experimentally during a case study of active compensation on the superconducting dipole magnets of LHC at CERN. In particular, the experiments for compensating the normal sextupole field error (B_3), which mainly degrade the field quality in a normal dipole (B_1), are illustrated.

The core of the compensation system in Fig. 1 is the equipment for harmonic measurements of coils [21]. A test station with the main aim of improving the bandwidth was developed specifically for measuring pulsed magnetic fields. In particular, high-speed rotating coils [28] and PXI Fast Digital voltage Integrator (FDI) [29] were developed.

Figure 3 Experimental set-up.

In Fig. 3, the experimental set-up for the case study of a LHC dipole is illustrated.

Both apertures of the cryo-assembly are equipped with a rotating shaft slightly longer than the dipole under test. The shaft is made by 12 ceramic segments, each one holding 3 tangential, equal, and parallel sensing coils. Typically, the first coil is used to measure the dipole field component (“absolute” signal). The connection in series opposition with a second coil allows the dipole to be cancelled (“bucked” signal) and ensures higher SNR for the measurement of harmonic error components [30]. The third coil is a spare. The last segment measures the dipole end field and the 0.11 m long sextupole corrector field. From each segment, two signals are available: absolute and bucked. Four segments are connected in series (supersegment) in order to generate an absolute and a bucked signal of a supersegment. Therefore on each shaft as a whole, 6 FDI’s are used to measure the 6 signals from the 3 supersegments synchronously. The twofold aims of such a configuration are to increase the signal level and to limit the number of integrators to six per aperture (three integrators for the absolute signals and three for the bucked ones).

Two high-speed Micro Rotating Units (MRU) rotate the shafts up to 8 turns per second in order

to acquire the coil signals at the desired time resolution. The trigger signal from angular encoders mounted in the MRU controls the integration time of the FDI's by means of a suitable PXI encoder board. The required compensation resolution is achieved by synchronizing the measured current ($I_{powering}$) and flux within a tolerance of 2 ms. This target is met by means of a Timing Board NI GPS PXI [31]. When a measurement is started, the Timing Board time-stamps the first triggers from the two channels of the encoder board with respect to its reference GPS. This allows the current readings, transmitted by the WorldFIP Gateway at 50 Hz, to be correctly synchronized with those of the sextupole ($I_{correction}$). The software for managing the measurement station and retrieving current readings is based on the Flexible Framework for Magnetic Measurements [32].

V. EXPERIMENTAL RESULTS

In this Section, (a) the *sextupolar field dynamic errors*, (b) the *analysis of the measurement error*, and (c) the *compensation results* are described.

A. Sextupolar field dynamic errors

The LHC dipole magnets are affected during their operation cycle (Fig. 4) by a hysteresis loop of the sextupole field component (Fig. 5 left).

Figure 4 Current phases in a powering cycle of a LHC dipole magnet.

In particular, the b_3 field multipole shows a slow *decay* in time domain during the low-field phase of particle injection (Fig. 5 right). The decay is explained as an effect of the decrease of the

filament magnetization of cable strands owing to a redistribution of the current between the strands [33]. Subsequently, as the field is ramped up for the beam acceleration, the b_3 *snaps back* to its initial value (referred as *snapback* phenomenon) within a small current interval. The resulting field ramp re-establishes the filament magnetization i.e. the full penetration of persistent currents. The snapback is the most difficult part of the hysteresis loop as a whole to compensate.

Figure 5 (Left) measured hysteresis loop, and (right) highlight of decay and snapback of the sextupolar error (b_3) in the time domain, during a powering cycle of a LHC dipole.

B. Analysis of the measurement error

In the proposed compensation, the achievable results depend mainly on a thorough understanding of the measurement errors. Data are analyzed turn by turn, thus the error sources are taken into account during a single turn of the equivalent coils of a supersegment. The predominating sources are:

- (i) *Integrator offset*: An offset at the input of the digital integration generates an additive ramp in the output. In the Fourier domain, this produces components on both normal and skew harmonics. Such an effect concerns the computed multipoles from both absolute and bucked coil signals (see Section IV). The typical offset of the Fast Digital Integrator for a fullscale of ± 10 V is ± 7 ppm [34]. The resulting effect on *normal* harmonics (cosine terms) is maximum (e.g. ± 0.4 ppm of b_3) when the Fourier analysis starts from the null value of the signal over a turn, and minimum when the analysis starts from the maximum signal value (this is the opposite for *skew* terms).
- (ii) *Main field variation during ramp*: The variation of the main field during a coil turn affects the measured value i.e. the harmonic terms obtained after the Fourier analysis.

This is referred to in metrology as “intrinsic uncertainty of measurand” or “definitional uncertainty” [35]. In the measurement conditions considered, the field variation over a turn generates an error up to ± 1000 ppm of b_1 and ± 0.3 ppm of b_3 . The effect on the higher order harmonics can be neglected due to the high bucking ratio, about 1000, of the measurements coils.

On this basis, the capability of compensating b_3 down to 2 ppm is achieved by constraining the overall measurement uncertainty to below ± 1 ppm. By assuming the typical measurement conditions to be measuring shaft rotation speed 1 turn per second with 512 samples per turn of the flux signal, and a current ramp rate of 10 A/s, the residual uncertainty is shown not to exceed ± 0.8 ppm.

C Compensation achieved on a spare magnet

The measurement system (Fig. 3) was configured in order to provide suitable reference measurements for LHC [36]. The measurement setup and the overall procedure of compensation were extensively tested on a spare LHC magnet in the test station SM18 [37]. Due in particular to cryogenic constraints, such tests require lengthy preparation and are resource intensive. The goal is to improve the FiDeL magnetic model based on the measurements carried out during the reception test of the LHC magnets with a measurement system delivering only values for quasi static field.

The results analyzed here below are based on a maximum current of 6 kA in the main dipole, corresponding to the beam energy in LHC today. Measurements with a maximum current of 11.8 kA have also been performed. The cycle parameters are selected in order to maximize the snapback amplitude [25]: $I_{\text{prep}}=0$ A, $t_{\text{pre}}=0$ s, $dI/dt=10$ A/s, $t_{\text{FT}}=1000$ s, and $t_{\text{inj}}=1000$ s. In Fig. 6, the powering current of the dipole under test for the compensation of b_3 is illustrated.

The superconducting sextupole corrector was characterized according to the analytical formulation in Section II.A, equation (5). The value of the obtained transfer function is $95.5 \mu\text{Tm/A}$, compatible with the design value and previous measurements. A typical nonlinearity of $3 \mu\text{Tm/A}$ (assessed as the rms of the linear regression residuals) also indicates a satisfying linearity, mandatory for the correct compensation of the sextupole into the dipole.

Fig. 7a demonstrates the effectiveness of the whole compensation procedure: the b_3 multipole in the aperture 2 of the dipole under test is plotted as a function of the current in the main dipole, first without correction, then with a first and a second correction.

Figure.6 Powering cycle of the LHC dipole in the validation of the proposed compensation.

In Fig. 7b, the current for the sextupole correction as a function of time, computed at the first iteration, is shown (the dipole current is also shown for clarity).

Figure. 7 (a) Results from compensation measurements (3 runs of the proposed procedure), and (b) computed sextupole corrector current (first run).

Figure 8 is a zoom of Fig.7a, illustrating the high level of compensation achieved, where in particular the dynamic behavior of the multipole is highlighted. At the first iteration, an average of b_3 of about 16 ppm with a spread of 2 ppm was achieved. Therefore, at the second iteration, the powering current of the corrector was biased correspondingly by a DC value of 0.12 A, according to (4). Then, an average b_3 of about 6 ppm, with a spread of 2 ppm, was reached. This result highlights the capability of the proposed iterative approach to keep the spread below 2 ppm and to reach significant shifts of the curve toward the zero.

Figure 8 Zoom of Fig. 7: achievement of the compensation target.

V. CONCLUSIONS

A system for the active compensation of field errors in superconducting magnets is presented. A generic iterative procedure based only on integral field measurements is tested and results in a residual uncertainty below ± 2 ppm of the main field. As an experimental case study, the sextupolar multipole, unavoidable in a LHC superconducting dipole magnet, is compensated to a high degree of precision by a specifically developed system. The experimental results show the effectiveness of the approach proposed and its potential as a new reference tool for improving the overall field quality of superconducting magnets.

Further work will be focused on (i) the implementation of the closed loop configuration of the system in order to automate the procedure, and (ii) experiments on Nb_3Sn magnets in the framework of a comprehensive investigation of the new technology for the future [38]-[39].

ACKNOWLEDGMENTS

Authors thank Luca Bottura, Marco Buzio, and Juan Garcia Perez for their useful suggestions, Guy Deferne, Peter Galbraith and David Giloteaux for supporting the tests, Alessandro Raimondo and Evgeny Zorin for making possible a large part of the work.

REFERENCES

- [1] P. J. Bryant, CAS - CERN Accelerator School: 4th General Accelerator Physics Course, CERN Publishing, Geneva, 1990, pp. 1 – 16.
- [2] L. Rossi, Elsevier Cryog. 43 (2003) 281-301.
- [3] L. D. Cooley; A. K. Ghosh; and R.M. Scanlan, IOP Supercond. Sci. and Technol.18 (2005) R51 – R65.
- [4] A. Devred, S. A. Gourlay, A. Yamamoto, IEEE Trans. on Appl. Supercond. 15 (2005) 1192 – 1199.
- [5] V.S. Kashikhin, N. Andreev, J. DiMarco, S. Feher, V.V. Kashikhin, M. Lamm, I. Novitski, D. Orris, P. Schlabach, C. Sylvester, M. Tartaglia, G. Velez, A.V. Zlobin, IEEE Trans. on Appl. Supercond. 14 (2004) 287 – 290.
- [6] K.-H. Mess, P. Schmüser, S. Wolff, Superconducting Accelerator Magnets, World Scientific Publishing, London, 1996, pp 147 – 164.
- [7] G.V. Velez, G. Ambrosio, G. Annala, P.Bauer, R. Carcagno, J.DiMarco, H. Glass, R. Hanft, R. Kephart, M.Lamm, M. Martens, P.Schlabach, C. Sylvester, M. Tartaglia, J. Tompkins, Measurements Of Field Decay And Snapback Effect On Tevatron Dipole And Quadrupole Magnets, Proceedings of Particle Accelerator Conference, Knoxville, Tennessee, May 16-20, 2005.
- [8] J. Wei, R. Gupta, M. Harrison, A. Jain, S. Peggs, P. Thompson, U. Trbojcevic, P. Wanderer ,Real-World Sorting Of RHIC Superconducting Magnets, Proceedings of Particle Accelerator Conference, New York, NY, March 27- April 02, 1999.
- [9] K. Wille, The Physics of Particle Accelerators: An Introduction, Oxford University Press, Inc. New York, 2000, pp. 44 – 135.
- [10] B. Warmbein, Inside Story: End of an era - HERA switches off, 08/21/2007, CERN Currier, <http://cerncourier.com/cws/article/cern/30898> available on 01/19/2011.
- [11] B. Holzer, C. Montag, Reproducibility and Predictability of Persistent Current Effects in HERA Proton Storage Ring, Proceedings of European Particle Accelerator Conference, Vienna, Austria, June 26-30, 2000.
- [12] D. McGinnis, Fermilab Tevatron Operational Status, Proceedings of Particle Accelerator Conference, Knoxville, Tennessee, May 16-20, 2005.
- [13] M. Martens, Tune and Coupling Drift Compensation During the Tevatron Injection Porch, Proceedings of Particle Accelerator Conference, Portland, Oregon, May 12-16, 2003.
- [14] P. Bauer, M. Lamm, G. Lorenz, J. Nogiec, T. Peterson, R. Sood, W. Soyars, C. Sylvester, M. Tartaglia, G. Velez, Cost Estimation for a Tevatron Reference Magnet System, Fermilab Internal Notes TD-02-042, February 02, 2004.
- [15] G. V. Velez, R. Carcagno, J. DiMarco, S. Kotelnikov, M. Lamm, A. Makulski, V. Maroussov, R. Nehring, J. Nogiec, D. Orris, O. Poukhov, F. Prakoshyn, P. Schlabach, J. C. Tompkins, IEEE Trans. on Appl. Supercond 16 (2008) 1374 – 1377.
- [16] The Large Hadron Collider – Design Design Report, <http://lhc.web.cern.ch/LHC/LHC-DesignReport.html>, available on 03/08/2010.
- [17] N. Sammut, L. Bottura, and J. Micallef, APS Phys. Rev. ST Accel. Beams 9 (2006) 012402.
- [18] P. Xydi, N. Sammut, R. A. Fernandez, L. Bottura, G. Deferne, M. Lamont, J.Miles, S. Sanfilippo, M. Strzelczyk, W. Venturini Delsolaro, A Demonstration Experiment for the Forecast of Magnetic Field and Field Error in The Large Hadron Collider, Proceeding of European Particle Accelerator Conference, Genova, Italy, June 23-27, 2008.
- [19] E. Todesco, N. Aquilina, B. Auchmann, L. Bottura, M. Buzio, R. Chritin, G. Deferne, L. Deniau, L. Fiscarelli, P. Hagen, J. Garcia Perez, M. Giovannozzi, M. Lamont, G. Montenero, G. Muller, M. Pereira, S. Redaelli, V. Remondino, N. Sammut, F. Schmidt, R. Steinhausen, M. Strzelczyk, R. Tomas, W. Venturini Delsolaro, J. Wenninger, R. Wolf, The Magnetic Model of the LHC in the Early Phase of Beam Commissioning, International Particle Accelerator Conference, Kyoto, Japan, May 23-28, 2010.
- [20] L. Evans and P. Bryant, IOP J. of Instrum. 3 (2008) S08001.
- [21] J. Billan, L. Bottura, M. Buzio, G. D'Angelo, G. Deferne, O. Dunkel, P. Legrand, A. Rijllart, A. Siemko, P. Sievers, S. Schloss, L. Walckiers, IEEE Trans. on Appl. Supercond. 10 (2000) 1422 – 1426.
- [22] T. Pieloni, S. Sanfilippo, L. Bottura, M. Haverkamp, A. Tikhov, E. Effinger, E. Benedico, N. Smirnov, IEEE Trans. on Appl. Supercond. 14 (2004) 86 – 89.
- [23] A. K. Jain, CAS - CERN Accelerator School: Measurement and Alignment of Accelerator and Detector Magnets, CERN Publishing, Geneva, 1998, pp. 1 – 26.
- [24] A. Devred, CAS - CERN Accelerator School: Measurement and Alignment of Accelerator and Detector Magnets, CERN Publishing, Geneva, 1998, pp. 43 – 78.
- [25] N. Sammut, L. Bottura, P. Bauer, G. Velez, T. Pieloni, J. Micallef, APS Phys. Rev. ST Accel. Beams 10 (2007) 082802.
- [26] M. Harrison, S. Peggs, T. Roser, Annual Rev. of Nucl. and Part. Sci. 52 (2002) 425 – 469.
- [27] P. Arpaia, M. Buzio, L. Fiscarelli, G. Montenero, J. Garcia Perez, L. Walckiers., Compensation of Third-Harmonic Field Error in LHC Main Dipole Magnets, IEEE Instrumentation and Measurement Technology Conference, Austin, May 3-6, 2010.
- [28] N. R. Brooks, L. Bottura, J. G. Perez, O. Dunkel, L. Walckiers, IEEE Trans. on Appl. Supercond. 18 (2008) 1617 – 1620.
- [29] P. Arpaia, A. Masi, G. Spiezia, IEEE Trans. on Instrum. and Meas. 56 (2007) 216 – 220.
- [30] A. K. Jain CAS - CERN Accelerator School: Measurement and Alignment of Accelerator and Detector Magnets, CERN Publishing, Geneva, 1998, pp. 175 – 217.
- [31] NIPXI-Timing Board 6682, <http://sine.ni.com/nips/cds/view/p/lang/en/nid/203944> available on 6/07/2010.
- [32] P. Arpaia L. Bottura, M. Buzio, D. Della Ratta, L. Deniau, V. Inglese, G. Spiezia, S. Tiso, L. Walckiers, A Flexible Framework for generating Magnetic Measurement Automatic Systems at CERN, IEEE Instrumentation and Measurement Technology Conference, Warsaw, Poland, May 1-3, 2007.
- [33] R. Wolf, The Decay of the Field Integral in Superconducting Accelerator Magnets wound with Rutherford Cables, 15th International Conference on Magnet Technology, Beijing, China, October 20-24, 1997.

- [34] G. Spiezia, A Fast Digital Integrator for magnetic measurements, PhD Thesis, http://www.fedoa.unina.it/3392/1/spiezia_giovanni_ingegneria_elettrica_xxi.pdf available on 11/25/2010.
- [35] Working Group 2 of the Joint Committee for Guides in Metrology, JCGM 200: 2008 International vocabulary of metrology — Basic and general concepts and associated terms (VIM), http://www.bipm.org/utls/common/documents/jcgm/JCGM_200_2008.pdf available on 01/18/2010.
- [36] S. Amet, L. Bottura, L. Deniau, L. Walckiers, IEEE Trans. on Appl. Supercond. 12 (2002) 1497 – 1421.
- [37] V. Chohan, M. Buzio, G. De Rijk, J. Miles, P. Pagnat, V. Remondino, S. Sanfilippo, A. Siemko, N. Smirnov, B. Vullierme, L. Walckiers, Testing of the LHC Magnets in Cryogenic Conditions: Current Experience and Near Future Outlook, Proceedings of Particle Accelerator Conference, Lucerne, Switzerland, July 5-9, 2004.
- [38] P. Wanderer, Nb3Sn Magnet Development For LHC Luminosity Upgrade, Workshop on Accelerator Magnet Superconductor Design and Optimization, Geneva, Switzerland, May 19-23, 2008.
- [39] H. Piekarz, IOP J. of Instrum. 4 (2009) P08007.